Attorney Docket: 91436-344

09968402.120301

APPLICATION

FOR

UNITED STATES LETTERS PATENT

TITLE: COMMUNICATION USING SIMULTANEOUS ORTHOGONAL SIGNALS

APPLICANT: David G. STEER, Koon Hoo TEO, and William R. KIRKLAND

COMMUNICATION USING SIMULTANEOUS ORTHOGONAL SIGNALS

FIELD OF THE INVENTION

The present invention relates to communication and, more particularly, to communication using simultaneous orthogonal signals.

BACKGROUND

Typically, in radio communications systems, an attempt is made to use radio transmission techniques (including modulation, coding and antenna processing) that are suited to the channel conditions. By doing so, the radio channel is used efficiently.

To this end, radio transmission techniques are traditionally first chosen and then designed into wireless communication equipment based on an expected performance of a channel that the equipment will be using to communicate. The radio transmission techniques may also be chosen based on a need to deliver a guaranteed level of service, which may be, for example, defined by a data rate, an error rate or a combination thereof. As channel conditions are typically described by statistical functions that vary over time, the channel may change considerably during the use of the equipment. The traditional approach to choosing radio transmission techniques usually results in a conservative design that is reliable, but does not use the full potential channel capacity. Often the radio channel performs better than the worst-case conditions. Where wireless communication equipment is designed with the worst-case channel conditions in mind, the radio transmission technique chosen is often too conservative. That is, not as much data is sent through the channel as could be sent using modulation and/or coding techniques different from the chosen techniques. However, to maintain a guaranteed performance in the worst-case channel conditions, such conservative choices may be necessary.

In modern radio systems, the radio transmission techniques may be dynamically adapted to suit the channel conditions at the time of transmission. The equipment may be designed with a capability to adapt the radio transmission techniques quickly to respond to changes in the channel conditions. The response

may include changes in the modulation techniques, coding techniques or antenna configurations for, say, beam tracking. Typically this adaptation involves a feedback control loop in which the channel conditions are measured at a remote receiver.

Channel conditions may, for instance, include a carrier to interference ratio or a data error rate. Measurements of these channel conditions may be signaled from the remote receiver to a transmitter so that the transmitter may adjust radio transmission parameters, such as power level, coding technique, modulation technique and antenna processing, to suit the signaled channel conditions. As the channel conditions vary over time, the radio transmission techniques may be adapted to suit the conditions reflected in the most recently received measurements. Thus, improved system performance may be achieved. System performance may be, for example, measured in terms of an amount of data throughput or a degree of interference with adjacent systems.

This adaptive communication technique is particularly suited to wireless Internet applications where the transmission of data may be delayed in time to await more favorable channel conditions. Advantageously, a constant user bit rate, which is a requirement of traditional radio systems, may not be a requirement of wireless Internet applications. It may also be important to improve the efficiency of frequency reuse (the simultaneous use of a frequency for two or more purposes) through, for example, antenna beam tracking.

One difficulty with this adaptive technique, however, is the requirement to estimate the current channel conditions. The adaptive technique provides the best performance when the channel conditions can be accurately determined. However, the channel conditions can change rapidly with time, particularly in a mobile communications environment, and the channel conditions may change significantly within a few milliseconds of being measured. The measurements may, thus, be of little benefit to the adaptive technique after the delay needed for the measurements to be signaled from the receiver to the transmitter. In a typical indoor office environment, measurements have shown that a channel may be completely decorrelated after about ten milliseconds (at a 900 MHz transmission frequency). Thus, the feedback control loop for the adaptive technique must be able to take

measurements and provide the measurements to the transmitter within a few milliseconds for the information to be useful. Other studies have shown that a significant portion of the advantage of adaptive modulation and coding is lost if the channel information is old.

A traditional approach to (two way) radio system design places the two directions of transmission in different frequency channels. This separation of the transmission and reception frequency, known as Frequency Division Duplexing (FDD), is necessary to permit the radio apparatus to adequately separate the relatively strong local transmissions from the relatively (very) weak signals received from the other end. Unfortunately, because the receiver is receiving on a channel that is well separated, in frequency, from the channel used by a related transmitter, the channel conditions measured by the receiver may not be suitable for adapting the radio transmission techniques for the transmitter.

SUMMARY

By using orthogonal signals for each direction of communication on a communication channel, each end of a communications link using the channel may transmit and receive simultaneously in the same frequency band. Additionally, a receiver may take measurements of channel conditions. These measurements may be used to adapt the transmission techniques used in the transmitter to suit the measured channel conditions. Advantageously, this adaptation can occur without the delay necessary for reporting of conditions that is characteristic of traditional adaptive communications systems.

This technique enables measurements of channel conditions to be made simultaneously with the communications. Thus, this technique may provide a communications endpoint an ability to generate measurements of the communications channel conditions that are more accurate and timely than those used in known duplexing techniques. These measurements enable improved performance to be achieved by communications systems that make use of channel information to adapt transmission techniques. Such transmission techniques include modulation, coding, beam tracking, space-time coding and other antenna processing

techniques. This technique also allows for asymmetric uplink and downlink data flows.

In accordance with an aspect of the present invention there is provided a method of communicating over a communications channel. The method includes receiving a received signal that includes a remotely transmitted signal, where the remotely transmitted signal is in a given frequency band and transmitting, concurrent with the receiving, a locally transmitted signal in the given frequency band, where the locally transmitted signal is substantially orthogonal to the remotely transmitted signal.

In accordance with another aspect of the present invention there is provided an apparatus for communicating over a communications channel. The apparatus includes a receiver for receiving a received signal that includes a remotely transmitted signal, where the remotely transmitted signal is in a given frequency band and a transmitter for transmitting, concurrent with the receiving, a locally transmitted signal in the given frequency band, where the locally transmitted signal is substantially orthogonal to the remotely transmitted signal.

In accordance with a further aspect of the present invention there is provided a radio communication system. The radio communication system includes a base station and a mobile terminal. The base station includes a base station receiver for receiving a base station received signal that includes a mobile terminal transmitted signal, where the mobile terminal transmitted signal is in a given frequency band and a base station transmitter for transmitting, concurrent with the receiving, a base station transmitted signal in the given frequency band, where the base station transmitted signal is substantially orthogonal to the mobile terminal transmitted signal. The mobile terminal includes a mobile terminal receiver for receiving a mobile terminal received signal that includes the base station transmitted signal and a mobile terminal transmitter for transmitting, concurrent with the receiving, the mobile terminal transmitted signal.

Other aspects and features of the present invention will become apparent to those of ordinary skill in the art upon review of the following description of specific embodiments of the invention in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

In the figures which illustrate example embodiments of this invention:

FIG. **1** illustrates a radio communications system including base stations and mobile terminals for use with an embodiment of the present invention;

FIG. **2** illustrates an arrangement of transmitter and receiver sub-carrier spectra according to an embodiment of the present invention;

FIG. **3** illustrates, in an alternative arrangement to that of FIG. **2**, transmitter and receiver sub-carrier spectra according to an embodiment of the present invention;

FIG. **4** schematically illustrates a transceiver apparatus for a base station of FIG. **1** according to an embodiment of the present invention;

FIG. **5** schematically illustrates a transceiver apparatus for a mobile terminal of FIG. **1** according to an embodiment of the present invention;

FIG. **6** schematically illustrates, in an alternative to the transceiver of FIG. **4**, a transceiver apparatus for a base station of FIG. **1** according to an embodiment of the present invention; and

FIG. **7** schematically illustrates, in an alternative to the transceiver of FIG. **5**, a transceiver apparatus for a mobile terminal of FIG. **1** according to an embodiment of the present invention.

DETAILED DESCRIPTION

A radio communications system **100** is illustrated in FIG. **1**. A pair of base stations, namely a first base station **102A** and a second base station **102B** (referred to hereinafter individually or collectively as **102**), are connected to a mobile

communications network **104**. The base stations **102** are arranged with coverage for use of mobile terminals **106**, examples of which are shown as a first mobile terminal **106X** and a second mobile terminal **106Y**. The mobile terminals **106** communicate with the base stations **102**, and hence the mobile communications network **104**, via two-way radio transmissions. These two-way transmissions, for example, can support a bi-directional flow of data between the mobile terminal **106** and a server (not shown) in the mobile communications network **104**, or a two-way speech conversation. A controller unit **108** is included in the mobile communications network **104** for supervising the base stations **102**.

Components of a base station transceiver apparatus **400** that is part of the base station **102** are illustrated in FIG. **4**, according to one embodiment of the present invention. User data that is to be transmitted is first received at an adaptive processor **402**. The adaptive processor **402** also receives input from a channel estimation processor **404**. Output from the adaptive processor **402** may be passed to a base station transmitter **405** where the output is applied to an Inverse Fast Fourier Transform (IFFT) **406** along with further input to identify the desired zeroes of a digital output signal. The digital output signal from the IFFT **406** is received by a digital to analog converter (DAC) **408** where the signal is converted to an analog signal. This analog signal is used to modulate a radio frequency at a transmit radio frequency (RF) converter **410**. The modulated radio frequency signal is then passed to a power amplifier **412** for amplification before being transmitted through the use of a transmit antenna **414**. The transmitted signals are also monitored by a variable gain amplifier **416**.

Signals are received at the base station transceiver apparatus **400** at a receive antenna **418**. At the input to a base station receiver **419**, a low noise amplifier (LNA) **420** compares these received signals with an error signal from the variable gain amplifier **416**. This comparison is achieved through the arrangement of the LNA **420** as a differential amplifier and allows signals from the mobile terminal **106** to be distinguished from those signals being transmitted at the transmit antenna **414**. The output of the LNA **420** is received at a receive RF converter **422** to remove the RF component of the signal. The analog signal at the output of the receive RF converter **422** is converted to a digital signal by the an analog to digital converter

(ADC) **424**. The digital version of the received signal is then passed to a Fast Fourier Transform (FFT) **426** to extract the information available in the Fourier transform of the signal. This information is shared among the channel estimation processor **404**, a transmitted signal suppression controller **430** and a user data decoder **428**. It is the transmitted signal suppression controller **430** that controls the gain on the variable gain amplifier **416** so as to appropriately remove the transmitted signals from the received signals. The output of the user data decoder **428** is a decoded version of the information sent from the mobile terminal **106**.

Components of a mobile transceiver apparatus **500** that is part of the mobile terminal **106** are illustrated in FIG. **5**, according to one embodiment of the present invention. User data that is to be transmitted is first received at an adaptive processor **502**. The adaptive processor **502** also receives input from a channel estimation processor **504**. Output from the adaptive processor **502** may be passed to a mobile transmitter **505** where the output is applied to an Inverse Fast Fourier Transform (IFFT) **506** along with further input to identify the desired zeroes of a digital output signal. The digital output signal from the IFFT **506** is received by a digital to analog converter (DAC) **508** where the signal is converted to an analog signal. This analog signal is used to modulate a radio frequency at a transmit radio frequency (RF) converter **510**. The modulated radio frequency signal is then passed to a power amplifier **512** for amplification before being transmitted through the use of a transmit antenna **514**. The transmitted signals are also monitored by a variable gain amplifier **516**.

Signals are received at a receive antenna **518**. At the input to a mobile receiver **519**, a low noise amplifier (LNA) **520** compares these received signals with an error signal supplied by the variable gain amplifier **516**. This comparison is achieved through the arrangement of the LNA **420** as a differential amplifier and allows signals from the base station **102** to be distinguished from those signals being transmitted at the transmit antenna **514**. The output of the LNA **520** is received at a receive RF converter **522** to remove the RF component of the signal. The analog signal at the output of the receive RF converter **522** is converted to a digital signal by the an analog to digital converter (ADC) **524**. The digital version of the received signal is then passed to a Fast Fourier Transform (FFT) **526** to extract the

information available in the Fourier transform of the signal. This information is shared among the channel estimation processor **504**, a transmitted signal suppression controller **530**, a symbol timing and frequency controller **532** and a user data decoder **528**. It is the transmitted signal suppression controller **530** that controls the gain on the variable gain amplifier **516** so as to appropriately remove the transmitted signals from the received signals at the LNA **520**. The output of the user data decoder **528** is a decoded version of the information sent from the base station **102**. The symbol timing and frequency controller **532** communicates with the IFFT **506** and the transmit RF converter **510** for controlling symbol timing and sub-carrier center frequency values.

In overview, providing continuous reception and transmission within the same channel may be achieved by arranging the signals being transmitted to be orthogonal to those being received. Thus, each end of a radio communications link may simultaneously receive signals from the other end and transmit signals to the other end. Furthermore, this simultaneous reception and transmission may be performed while estimating the channel conditions. The delay between determining an estimate of the channel conditions and the use of that estimate is the time needed for measurement of the channel conditions at the base station receiver **419** (which is collocated with the base station transmitter **405**) and the calculation of an appropriate adaptation of radio transmission techniques. Thus, an optimum advantage can be taken of adaptive communication, as the channel estimation information is more current than is available with other duplexing techniques.

The channel estimation process and the process of adaptation of radio transmission techniques operate together to measure and estimate the channel conditions and to adapt the radio transmission techniques to suit the latest conditions of the channel. In a preferred technique, data is modulated onto a set of sub-carriers at predictable frequencies. To enable the channel to be estimated, pilot signals may be introduced by the base station transmitter **405**. Typically, a sub-set of the sub-carriers, known as pilot sub-carriers, are selected and modulated in a pattern known to the mobile receiver **519**. Signals on pilot sub-carriers received the mobile receiver **519** are compared with expected signals in the channel estimation processor **504** at the mobile terminal **106**. For example, if a particular measurement of a received pilot

signal is lower in strength than the last measurement of the same pilot signal, the channel estimation processor **504** can conclude that the channel has deteriorated and indicate to the adaptive processor **502** that a stronger coding and/or lower level of modulation may be necessary for the next transmissions. Similarly, if the particular received pilot signal has strengthened since it was last measured, then a less robust coding and/or higher level of modulation may be selected by the adaptive processor **502**.

As the full transmission signal occupies a significant bandwidth, such as 5 MHz, the channel effects on the sub-carriers will be different in different parts of the channel. For example, the channel may be logically divided into 30 sub-carriers, numbered 1-30. In operation, sub-carriers 2 and 4 may be affected by the channel differently than channels 20 and 30. On the other hand, sub-carriers 1, 3 and 5 may be expected to be affected by the channel in a similar way to 2 and 4. By introducing a sufficient number of pilot signals on sub-carriers suitably distributed across the channel, the effects of the channel may be determined for nearby sub-carriers. For example, with pilot signals available in sub-carriers 20 and 30, the effect on the sub-carriers in-between (21-29) may be estimated by a linear interpolation from the measurements of the pilots at 20 and 30. For the mobile radio channel, it has been found that using about 10% of the sub-carriers for pilot signals provides sufficient resolution to estimate the channel without an undue loss of capacity (as the pilot sub-carriers are not available to carry user payload data). A suitable number and distribution of pilot sub-carriers is shown in the Digital Video Broadcasting (DVB) Standard found in European Telecommunications Standards Institute (ETSI) standard EN 300-744 (hereby incorporated herein by reference). Chapter five of Richard van Nee and Ramjee Prasad, "OFDM for Wireless Multimedia Communications", Artech House publishers 2000, ISBN 0-89006-530-6 also discusses the principles of channel estimation for Orthogonal Frequency Division Multiplexing (OFDM) radio systems.

In the DVB standard, there are both "fixed" and "wandering" pilot signals. The fixed pilot signals remain with the same sub-carrier for all transmitted symbols. The wandering pilot signals change their sub-carrier location, in a sequence known to the receiver, from symbol to symbol. Consequently, the channel estimation may not only

involve interpolation between sub-carriers in frequency but also interpolation between sub-carriers in time. This two-dimensional interpolation permits a better estimate of the channel for each sub-carrier.

Orthogonality of the transmitted and received signals can be achieved in a number of ways. These ways include traditional Time Division Duplexing (TDD), Code-Division Duplexing and Orthogonal Division Duplexing (described hereinafter). The important property of the orthogonality, in this context, is that the integral of the received signal together with a suitable function over an interval of time is zero for all except the desired signal.

Orthogonality may be defined more formally as follows:

A set of functions u_1, u_2, u_3 ... u_n are said to be orthogonal functions if the integral over some interval of the product of u_n and the conjugate of u_m is zero when n and m are not equal. The conjugate operation is needed for complex valued functions. The function u_m and the conjugate of u_m are equivalent for real functions. Further details of orthogonal functions and their relation to Fourier analysis may be found in chapter 2 of Harry Davis, "Fourier Series and Orthogonal Functions", Allyn and Bacon Inc., Publishers, Library of Congress catalogue 63-13527.

Traditional TDD provides orthogonal signals by requiring that transmission and reception occur in designated different time intervals. In contrast, the following two methods for providing orthogonal signals allow for simultaneous transmission and reception. Accordingly, the transmission techniques may be dynamically adjusted based on estimates of the characteristics of the channel that are much more accurate and timely. That is, estimates of the characteristics of the channel obtained from analysis of the received signal may be used immediately to adjust transmission techniques, rather than waiting for the next transmission interval. In the case of TDD, the functions that assure orthogonality are those that are only non-zero during different intervals of time for each direction of transmission. This defines the uplink and downlink transmission burst time slots.

One way to make orthogonal signals is to use orthogonal spreading codes at the transmitter and the receiver. Although this is done in CDMA mobile radio

systems, the channel for transmitting is separate from the channel for receiving. For a more complete description of CDMA, see, for example, Gordon L. Stüber, “Principles of Mobile Communication” (hereby incorporated herein by reference) beginning on page 6 and later sections. So-called Walsh functions, used in the Telecommunications Industry Association standard IS-95, for example, may be used to generate orthogonal CDMA codes. Code-division duplexed signals, transmit (Tx) and receive (Rx), may then be separated through the use of a correlator at the receiver. With the herein proposed arrangement, the two signals overlap in the radio spectrum and the correlator must have sufficient gain (i.e., the orthogonal codes must have sufficient spreading gain) to allow the weak received signal to be separated from the strong, locally generated, transmitted signal. While such codes are practical, the chip timing at each of the two ends must be synchronized in time for optimum orthogonality. A drawback of the orthogonal code-division duplexing technique is a difficulty in determining a true signal to noise ratio in the received signal, as both the transmitted signal and the received signal occupy the same spectrum and the transmitted signal is the major source of interference. The functions that assure orthogonality in the case of Code Division Duplexing are typically complex valued time sequences that integrate to zero over the symbol time interval (as in the above integral definition). The Walsh functions used in CDMA systems are common examples of orthogonal CDMA sequences.

A preferred method to obtain orthogonal signals is to generate the transmitted signal in such a way that data is modulated onto “sub-carriers” at predictable frequencies across the assigned radio communications channel. At other predictable frequencies are “zeros” where there is no signal present. At each end of the radio link, the transmitted signal has zeros at the frequencies of the transmitted sub-carriers of the other end, and sub-carriers at frequencies of the zeros of the other end. The two sets of sub-carriers thus interleave and do not interfere with each other. We call this communication technique Orthogonal Division Duplexing, or “ODD”.

As the sub-carriers are spread throughout the channel in ODD, the receiver is able to determine channel conditions for the sub-carriers that are received. The

channel conditions for the transmission sub-carriers may then be estimated by interpolating between channel conditions of the received sub-carriers.

These transmissions may be made in a manner similar to that used for Orthogonal Frequency Division Multiplexing (OFDM). Traditional OFDM radio systems use frequency division duplexing with a transmit channel and a receive channel. Transmissions from a base station may be sent to multiple mobile terminals on predetermined sub-carriers of the transmit channel. Transmissions from the mobile terminals are received on predetermined sub-carriers in the receive channel. For OFDM, the sub-carrier frequency spacing and the symbol timing are carefully chosen such that the zeros of the transmitted spectrum of each sub-carrier fall on the center of the other sub-carriers. Thus, there is no interference between sub-carriers and each set of transmitted sub-carriers is said to be orthogonal to the other transmitted sub-carriers. An OFDM transmission is typically generated using an Inverse Fast Fourier Transform (IFFT) technique. Richard Van Nee and Ramjee Prasad, "OFDM for Wireless Multimedia Communications" (hereby incorporated herein by reference) describes a suitable method for setting the symbol timing, the sub-carrier spacing and the number of sub-carriers in each set.

For ODD, the sub-carrier frequency spacing and the symbol time are carefully chosen such that the zeros of the transmitted spectrum signal fall on the centers of the sub-carriers of the received spectrum. Thus there is no interference between sub-carriers and the signal is said to be orthogonal. To ensure the orthogonality of the sub-carriers, the frequency spacing of the sub-carriers may be selected to be equal to the reciprocal of the symbol duration.

In the case of ODD, the functions that assure orthogonality are created by the Fourier transform and the timing of the symbols. This defines a set of sub-carriers and using every second sub-carrier enables the two directions of transmission to be interleaved to form the uplink and downlink.

A transmitted signal appropriate for ODD (i.e., a transmitted signal with a comb structure of zeros and active sub-carriers that facilitates interleaving of the transmitted signal with a received signal) can be formed, for example, by arranging

that a zero value be supplied at all the even inputs to the base station IFFT **406**. At the mobile terminal **106**, an appropriate transmitted signal may be formed by entering zero for all the odd inputs to the mobile terminal IFFT **506**. This will cause every second sub-carrier to be zero and allow space for the interleaving of the two directions of transmission. Exemplary ODD transmit signals, generated by a base station **102** using the IFFT **506**, and receive signals are illustrated in FIG. **2**. As illustrated in a transmitter spectrum **202**, the base station transmitter **405** (FIG. **4**) transmits on the odd sub-carriers and, as illustrated in a receiver spectrum **204**, the mobile transmitter **505** (FIG. **5**) transmits such that the base station receiver **419** receives on the even sub-carriers.

Of course, while even/odd is one way to organize the sub-carriers, other patterns are possible (every third, random, etc.), subject to a constraint that the channel is suitably sampled across its width. Suitably sampled means that there are enough samples (i.e., received sub-carriers) of the channel across the frequency band to allow a good estimate of the channel to be made. This is an application of the Nyquist sampling theorem. Note that this technique also allows a different number of sub-carriers to be used in each direction, for instance, say one third of the sub-carriers dedicated to signals from the mobile terminal **106** to the base station **102** (uplink) and two thirds of the sub-carriers dedicated to signals from the base station **102** to the mobile terminal **106** (downlink), to match asymmetric traffic flows. This is often the case in the Internet service to a mobile end user.

Notably, this latter technique requires determining an amount of downlink traffic in the locally transmitted signal, determining an amount of uplink traffic in the remotely transmitted signal and determining a traffic ratio that is a ratio of the amount of downlink traffic to the amount of uplink traffic. The ratio of the number of sub-carriers dedicated to the downlink to the number of sub-carriers dedicated to the uplink may be arranged to be proportional to said traffic ratio.

In an alternative sub-carrier assignment technique, the center frequencies of the sub-carriers for the uplink and downlink may be selected from two pseudo-random but non-overlapping sets of candidate sub-carrier center frequencies. The sets may then be changed, perhaps as often as once every symbol duration (i.e., for

successive transmitted symbols), in a pseudo-random pattern known to the both the receiver and the transmitter. This technique may be called "frequency hopping" and may serve to reduce interference between adjacent cells.

FIG. **3** illustrates a sub-carrier arrangement in which more sub-carriers are assigned to a downlink spectrum **302** than an uplink spectrum **304** to allow the transmission of more data traffic in the downlink direction. This may be achieved by setting the appropriate inputs to the IFFT **406**, **506** in the transmitters **405**, **505** (FIGS. **4**, **5**) to zero to create the appropriate interleaving of the sub-carriers.

While the pattern of sub-carriers assigned for uplink and downlink may be fixed within the radio system **100**, the pattern of sub-carriers may also be changed dynamically to support, for example, changes in the traffic flow in the uplink and downlink directions. In such a dynamic arrangement, the controller unit **108** in the radio system **100** (FIG. **1**) may measure the traffic flow in each direction and act to increase or decrease the number of sub-carriers allocated to each direction, so that the allocation better accommodates the traffic requirements. The changes in the sub-carrier allocations would be signaled between the base station **102** and the mobile terminals **106** using signaling facilities inherent in the radio communications system. This signaling would occur before the changes in the sub-carrier allocations so that the two ends remain in synchronization. The allocation of sub-carriers may also be changed regularly, in a predetermined pseudo-random pattern to reduce the interference effects of the transmissions into adjacent cells in a multi-cell communications system. This is similar to "frequency hopping" used in some systems, for instance, the Global System for Mobile communication (GSM).

The changes in the allotment of sub-carriers to the uplink and the downlink would be effected relatively slowly in response to changes in the average traffic flows sensed by the controller unit **108**, of which there may be more than one in a given mobile communication network. Any changes in the sub-carrier allotment should be done fairly slowly, say, over period of minutes, as it may take time to ascertain average traffic flows and each of the mobile terminals **106** must be informed of the new allotments ahead of time so the base stations **102** and the mobile terminals **106** can all switch together to the new arrangement.

In the radio communications system **100** of FIG. **1**, there may be multiple base stations **102** and a multitude of mobile terminals **106**. While, generally, on the downlink (the link from the base station **102** to the mobile terminals **106**) all of the mobile terminals **106** will receive the same broadcast signals from the base station **102**, on the uplink (the link from the mobile terminals **106** to the base station **102**), more than one mobile terminal **106** may need to transmit at one time. With ODD, the uplink sub-carriers may be sub-divided among multiple mobile terminals **106**, with each mobile terminal **106** transmitting on a sub-group of the total available uplink sub-carriers. With this arrangement, for example, a single high-speed downlink service may be combined with many lower speed uplink services from the mobile terminals **106**. This provides a way to multiplex the traffic from many users together. In this case, the base station receiver **419** will be receiving signals from many mobile terminals **106** and may measure the channel conditions for each. The transmission adaptation process for the downlink will then, typically, be based on the worst of the measured channel conditions. This will guarantee service, but at the expense of reduced throughput as the system will be hampered by the conditions in the weakest uplink. Alternatively, the adaptation may ignore the weakest uplinks to concentrate on those uplinks that provide acceptable performance while performing retransmissions of data later on the weakest uplinks when their channel conditions have improved.

At the base station receiver **419**, the task of separating the received signal from the locally transmitted signals is made easier by their orthogonality. By virtue of the IFFT **406** used to generate a transmitted signal, there are no transmitted signals at the intended receive sub-carrier frequencies. The issue for reception is thus not one of filtering, but more simply, of dynamic range in the base station receiver **419**. The dynamic range of a particular receiver is a ratio of the strongest to the weakest signal that can be processed by the particular receiver.

The dynamic range may be addressed with several techniques. By employing separate Tx and Rx antennas, with suitably low coupling (perhaps with orthogonal polarization), the magnitude of the Tx sub-carriers can be considerably reduced in the base station receiver **419**. However, separate antennas are only suitable for low radio frequency operation. If the antennas are separated by more than about one

quarter wavelength or are of opposite polarization, then, particularly in a multi-path propagation environment, the radio channel conditions experienced by the two antennas may be uncorrelated. This will reduce the suitability of the measured channel characteristics for use to adapt the transmissions. As illustrated hereinafter, a preferred implementation is a single transmit/receive antenna. A single antenna arrangement is also more practical for the small, portable handsets typical of the mobile terminals **106**.

To further reduce the amount of signal in the receiver front end, the LNA **420** (FIG. **4**) may be arranged differentially, to subtract away much of the transmitted signal. In this arrangement, an error signal, which is an attenuated, inverted and slightly delayed version of the transmitted signal, is fed into the LNA **420** together with the signal from the receive antenna **418**. This serves to cancel out most of the transmitted sub-carriers, thereby reducing the range of amplitudes between the locally transmitted signals and the desired sub-carriers sent by the mobile transmitter **505**. Suitable high linearity and high dynamic range amplifiers and analogue-to-digital converters can then be constructed to sample the received signal. The FFT **426** may then be able to separate the orthogonal sub-carriers that are to be received from the orthogonal sub-carriers transmitted, and thus enable detection of the incoming data.

FIG. **4** illustrates the base station transceiver apparatus **400** for using the ODD technique. FIG. **4** shows a configuration with the transmit antenna **414** separated from the receive antenna **418** for clarity of explanation. On the transmission side, data to be transmitted to the mobile receiver **519** is received at the adaptive processor **402**. This data is coded and modulated using techniques chosen according to the latest information about the channel received from the channel estimation processor **404**. The coded bits may then be sent as the odd inputs to the IFFT **406** where the coded bits modulate the odd sub-carriers. The IFFT processes the samples of data to be transmitted (plus the pilot signals) that are organized in frequency space (i.e., represented by sub-carriers) and transforms these into a time sequence of samples that represent the composite base-band signal to be transmitted for the symbol interval. The even inputs may be set to zero to provide zero transmitted signal at the intermediate sub-carriers. The output time sequence

from the IFFT **406** is then converted to analog format by the DAC **408**, converted to the appropriate radio frequency for the assigned channel by the transmit RF converter **410**, amplified to a suitable level by the power amplifier **412** and sent to the transmit antenna **414** for transmission over-the-air to the mobile terminal **106**. In many cases, the RF conversion process performed by the transmit RF converter **410** and the power amplifier **412** also involves some filtering to confine the signals to the assigned channel.

As discussed above, an error signal that is a version of the transmitted signal may be coupled through the variable gain amplifier **416**, which may also be called an attenuator, to the differential input of the LNA **420**. A signal representative of the transmitted signal is typically taken from one of the internal stages of the power amplifier **412** to reduce the coupling between the transmit antenna **414** and the error signal. This avoids any other signals that may be incident on the transmit antenna **414** (including the desired signal from the mobile terminal **106**) from becoming part of the error signal.

The summation input of the LNA **420** is connected to the receive antenna **418**. This receive antenna **418** may be separated from the transmit antenna **414** and may be arranged with a different polarization to reduce coupling from the transmitted signal. The LNA **420** provides, as its output, the difference between its two inputs. Thus, the attenuated version of the transmitted signal provided though the attenuator coupling from the base station transmitter **405** (the error signal) is subtracted from the received signal (which includes a remotely transmitted signal, a locally transmitted signal and noise) from the receive antenna **418** leaving, substantially, the remotely transmitted signal from the mobile terminal **106** at the output of the LNA **420**.

The variable gain amplifier **416** provides a complex gain function enabling adjustment to both the amplitude and phase of the error signal coupled to the differential input of the LNA **420**. As the received signal may contain several delayed copies of the transmitted signal (due to multi-path reflections in the nearby environment) the variable gain amplifier **416** may also be provided with the capability to develop a composite of multiple attenuated and phase shifted copies of the

transmitted signal to feed to the differential input of the LNA **420**. Forming the multiple delayed copies of the transmitted signal is analogous to the operation of the equalizers that are sometimes used to process the received signal in other receivers. Although, in this case, the equalizer is working with the locally transmitted signal and is adapted by a transmit control suppression process.

The received signal is then down-converted to baseband by the receive RF converter **422** and sampled by the ADC **424**. Digital samples at the output of the ADC **424** are then processed by the FFT **426**, the output of which includes signals from each of the sub-carriers.

Information carried on the even sub-carriers becomes the user data (i.e., payload data) after decoding at the user data decoder **428**. The pilot sub-carriers are supplied, by the FFT **426**, to the channel estimation processor **404** so that an estimate of the channel conditions may be generated. Typically, the output of the channel estimation processor **404** would be a signal to noise (or signal to noise plus interference) ratio estimate for each of the sub-carriers (or at least groups of them). These estimates would then be used by the adaptive processor **402** to select a suitable coding and modulation technique (or an antenna processing configuration, etc.) for each sub-carrier (or group of sub-carriers). In this method, the channel information gained on a received symbol can be used for the next transmitted symbol.

The received sub-carriers (even) are not at the same sub-carrier frequencies as the ones used for transmission (odd). The received sub-carriers may be interleaved with the transmitted sub-carriers, however, and the channel estimation processor **404** may interpolate between the received sub-carriers to accurately estimate the conditions for the transmitted sub-carriers. This may be done, for example, by taking the average of the conditions for the two received sub-carriers on each side of a sub-carrier to be transmitted.

For the present example, the odd sub-carriers at the output of the FFT **426** represent the (undesired) locally transmitted sub-carriers. These should be as small as possible to minimize the effect of the locally transmitted signal on the dynamic

range of the LNA **420**. The odd outputs from the FFT **426** are coupled to the transmitted signal suppression controller **430**. The output of the transmitted signal suppression controller **430** is used to control the variable gain amplifier **416** coupling the error signal into the differential input of the LNA **420**. The transmitted signal suppression controller **430** may, for example, compute the average power of the odd received sub-carriers and, based on this average, adjust the gain of the variable gain amplifier **416** to minimize the computed average power. For instance, if the average power of the odd outputs increases, the attenuation through the variable gain amplifier **416** would be decreased in order to increase the amount of cancellation happening at the LNA **420**.

Returning to the actions of the adaptive processor **402**, a common way to adapt transmission techniques is to use a lookup table in which a preferred combination of transmission techniques (an adaptation mode) is provided for a number of ranges of signal to noise ratio estimates (received from the channel estimation processor **404**). It is a change in a received estimate to a value outside the range of the current adaptation mode that triggers a change in adaptation mode to be decided upon by the adaptive processor **402**.

Adaptive modulation and coding techniques are already used in the telecommunications industry with the changes being triggered by measurements made at the opposite end or based on channel traffic performance. The changes in the modulation and coding are typically communicated by the transmitter to the receiver through signaling channels and messages that are otherwise part of the radio communication system. In these systems, a message containing instructions for the modulation and coding to be used in the future is sent over the radio communications signaling channel to the receiver. This message usually indicates that at some specified or implicit time in the future, the modulation and coding will change to the new format. This technique introduces some delay in the format change due to the time needed for transmission and reception of the message. As another example, in the Digital Video Broadcast Standard, mentioned previously, a subset of the sub-carriers are allocated, much like the pilot sub-carriers, for use to signal the modulation and coding for the current transmission. These sub-carriers are referred to as the Transmission Parameter Sub-carriers (TPS). This technique is

preferable as it minimizes the delay for changes in format as the transmission parameter signals are contained with each symbol.

It has been earlier stated that the adaptable transmission techniques include modulation, coding, power level, beam tracking and space-time coding. The manner in which these transmission techniques may be adapted to the channel conditions is discussed in the following.

Taking into account a worst-case channel, a typical radio communication system may be arranged to use Quadrature Phase Shift Keying (QPSK) for modulating data on the transmitted carrier. However, where the modulation technique is adaptable to the measured channel conditions, the modulation technique may range from Binary Phase Shift Keying (BPSK), for a poor channel, through QPSK and 16-Quadrature Amplitude Modulation (16-QAM) to 64-QAM for a high quality channel.

The data sent over the radio system **100** is typically coded to protect against errors in the received signal. As part of the coding process, extra transmitted bits are sent which enable the detection and correction of errors by the receiver. There are a number of forms of coding some more suited to transmissions in which a lot of errors are expected and some for which few errors are expected. In a non-adaptive system, the coding technique is selected to suit one aspect of the channel conditions and the error performance of the communications varies depending on the actual channel conditions which may vary from very few induced errors to very many. In an adaptive system, such as that which is proposed herein, measurements are made of the channel performance or the error rate and, if the performance is unsatisfactory, another coding technique selected that is better matched to the channel conditions. In this technique, typically, the errors are held below the desired rate while the delivered data rate varies according to the channel conditions. Whenever the channel conditions are better than average, an adaptive system can achieve a higher data throughput than one which does not adapt to the channel conditions. The adaptation, however, is at the expense of more complexity in the transmitter and receiver and the need for additional signaling between the two to coordinate the changes in coding technique.

Through an analysis of two received sub-carriers, it may be seen that the part of the channel occupied by these sub-carriers is subject to fading. It may then be determined that the power level of the transmission sub-carrier, which lies at a frequency between the two received sub-carriers, should be increased.

In a simple radio system, a single antenna is used that provides coverage of a region. The region may include many desired users in addition to sources of interference or noise. The level of this interference is typically responsible for limiting the performance of the radio communications either in terms of capacity (i.e., the number of users than can be supported at once) or data rate (i.e., the maximum bit rate that can be delivered to a user). In these cases the desired signals and the interference must be separated by a process performed by the radio receiving apparatus. This process is equally applicable to communications from the base station to the mobile unit (downlink) and from the mobile to the base station (uplink). In beam tracking systems, an antenna array is used that enables the radio signals to be concentrated or focused in small regions of the coverage region. The antenna array may, for example, be directed to concentrate the gain (i.e., direct a beam) on the signals of one mobile unit while also reducing the interference from other sources (i.e., direct a null). These beam directing (tracking) operations may be directed either by simple direction (i.e., by sending the beam in a predetermined direction) or through a feedback technique in which, for example, the strength of the desired signal is measured and the beam direction controls adjusted to maximize the strength of the desired signal. These beam tracking systems have the advantage that they reduce the level of interference seen by the receiver and thus enable either more users to be accommodated within a given cell or better service (i.e., higher bit rates) for each user. However, this advantage is achieved at the expense of a more complex antenna structure containing multiple elements and the means to measure the performance and adjust beam steering controls to track the beam. Further discussion of antenna beam tracking techniques may be found in J.S. Thompson, P.M. Grant and B. Mulgrew, “Smart Antenna Arrays for CDMA Systems”, in the journal IEEE Personal Communications, October 1996, pp. 16-25.

Space-time coding is a technique that achieves higher throughput for a radio communications system through the use of antenna arrays at both the transmitter

and receiver. A radio communications system that utilizes a single antenna at each end of a radio link is limited to a single communications channel and this limits the capacity throughput. If there are multiple antennas at each end of the link, there is, in effect, an almost separate communications path between each antenna pair. As there are multiple paths available, the capacity of the system is increased in proportion to the number of antennas used. Space-time coding is a technique for creating multiple transmission signals to be sent from each of the multiple antennas to exploit the multiple transmission paths. Further details of the space-time coding techniques may be found in A. J. Paulraj and C. B. Papadias, "Space-Time Processing for Wireless Communications", in the IEEE Signal Processing Magazine, November 1997, pp. 49-83.

The mobile transceiver apparatus **500** for the mobile terminal **106** is shown in FIG. **5**. Again, for clarity in explanation, FIG. **5** shows separation between the transmit antenna **514** and the receive antenna **518**. The signal processing flow is similar to that occurring in the base station transceiver apparatus **400** of the base station **102** (FIG. **4**), except that the user data transmissions occur on the even sub-carriers and the data reception occurs on the odd sub-carriers (for the present example). Note also that, if polarization is used to assist separation of the transmit sub-carriers and the receive sub-carriers, the transmit antenna **514** and the receive antenna **518** will have polarization matching the base station format (i.e., the mobile receive antenna **518** will match the polarization of the base station transmit antenna **414**, and the mobile transmit antenna **514** will match the polarization of the base station receive antenna **418**).

Two additional processes involving symbol timing and frequency control are introduced for the mobile station.

The mobile terminal **106** determines the values of the frequencies of the sub-carriers of the base station transmitter **405** and adjusts the frequencies of the transmitted sub-carriers so that the transmitted sub-carriers of the mobile terminal **106** properly interleave with the sub-carriers received from the base station **102**. In this case, the mobile terminal **106** is a slave, for frequency control, to the base

station **102**. This is usually the case for a mobile communications system, as there are many more mobile terminals **106** than base stations **102**.

At the mobile terminal **106**, output from the FFT **526** is sent to the symbol timing and frequency controller **532** that may adjust the center frequency of transmission sub-carriers to interleave with the sub-carriers center frequencies of the signal received from the base station **102**. If the mobile terminal **106** is moving rapidly, then the frequencies of the sub-carriers transmitted by the base station transmitter **405** will be offset by a Doppler shift. This offset (or frequency error) will be a few Hertz, depending on the speed of the mobile terminal **106** in relation to the base station **102**. This frequency error cannot easily be compensated. However, the spacing of the odd sub-carriers may be made sufficient to accommodate such a small error without undue loss of orthogonality.

The mobile terminal **106** must also adjust the symbol timing of its transmissions to match the symbol timing of the transmissions sent by the base station **102**. This is necessary so that the transmission time used for each symbol by the mobile terminal **106** coincides with the transmission time used for each symbol by the base station **102**. This assists in maintaining orthogonality through the IFFT/FFT processing. There will be some error in the symbol timing due to the propagation time of the signals over the air. However, this error will typically be small and may be allowed for as part of a guard interval incorporated in the symbol transmissions. Alternatively, the base station transceiver apparatus **400** may estimate the symbol timing offset of the signals received from the mobile terminal **106** and signal this timing error to the mobile terminal **106**, using signaling mechanisms inherent in the radio communication system **100**. The mobile terminal **106** may then adjust its symbol timing to compensate for the transmission timing delays as is common in such communications systems.

To assist in the symbol timing and frequency control, the base station **102** may include in its transmissions a set of pilot sub-carriers. The symbol timing and frequency controller **532** may detect a frequency shift by searching for the locations of the pilot sub-carriers and adjust the frequencies of the locally transmitted sub-carriers to correct the offset. The pilot sub-carriers may also be used to detect the

symbol timing and used to correct the timing of the mobile station **106**. Chapter four of the book by Richard van Nee and Ramjee Prasad, "OFDM for Wireless Multimedia Communications" Artech House Publishers 2000, ISBN 0-89006-530-6 contains the details of synchronization used in OFDM transceivers.

Earlier it was noted that the preferred arrangement for the transceiver apparatus **400**, **500** includes a combined transmit and receive antenna. This is necessary to assure, at high radio frequencies (e.g., 1–5 GHz) typically used for mobile communications systems, that the transmission and reception radio propagation paths are the same. If the paths are the same, then the measurements made at the receiver can be used to adapt the transmissions effectively. The earlier illustrations (FIG. **4** and FIG. **5**) showed separate transmit antenna **414**, **514** and receive antenna **418**, **518**. FIG. **6** and FIG. **7** show a single-antenna base station transceiver apparatus **600** and a single-antenna mobile terminal transceiver apparatus **700**, respectively.

The signal processing and flow at the single-antenna base station transceiver apparatus **600** are the same as previously described in conjunction with the base station transceiver apparatus **400**. A single antenna **636**, however, is coupled to the power amplifier **412** and to the summation input of the LNA **420** by means of an isolator **634**. Devices, such as the isolator **634**, are commonly used in radio equipment and allow coupling of a single antenna to the base station transmitter **405** and the base station receiver **419** without undue coupling between the base station transmitter **405** and the base station receiver **419**. In the illustrations, the isolator **634** provides a low loss path from a T (for transmit) terminal to an A (for antenna) terminal and a high loss path (isolation) from the T terminal to an R (for receive) terminal. This isolates the base station transmitter **405** from the base station receiver **419** to some degree, but typically not perfectly (i.e., typically 20 dB isolation). Similarly the isolator **634** provides a low loss connection from the A terminal to the R terminal and a high loss connection from the A terminal to the T terminal. Of course, some of the energy that passed from the T terminal to the A terminal, will be radiated by the antenna **636**, reflected from objects nearby back to the antenna **636** and hence be coupled from the A terminal to the R terminal and into the base station receiver **419**. The isolator **634** must therefore be augmented by the differential LNA

420 in front end of the base station receiver **419** to remove the transmitted signal from the received signal. As the reflected signals will be delayed in time in reaching the base station receiver **419**, the variable gain amplifier **416** must provide suitable amplitude and phase adjustment to the error signal to enable the transmitted signal to be cancelled correctly. The variable gain amplifier **416** may also contain an equalizer function, as described earlier herein, to compensate for the multiple reflections of the transmitted signal.

Similarly, the signal processing and flow at the single-antenna mobile transceiver apparatus **700** are the same as previously described in conjunction with the mobile transceiver apparatus **500**. Like the single-antenna base station transceiver apparatus **600**, the single-antenna mobile transceiver apparatus **700** includes an isolator **734** for coupling a single antenna **736** to the power amplifier **512** and to the summation input of the LNA **520**.

As will be apparent to a person skilled in the art, although this technique of communication using simultaneous orthogonal signals is especially well adapted to the wireless radio communication environment, the channel over which signals are transmitted and received may well be a telephone line, a coaxial cable connection or any other communication channel.

In particular, the communication channel may be a digital subscriber line (DSL). Communication over a DSL channel does require channel estimation, but as the cables are fixed, the DSL channel does not have the dynamic problems that are faced in the wireless domain. Typically the DSL channel can be equalized once and then the compensation remains effective for a long time (hours or days). In the wireless domain the channel changes within milliseconds so the channel must be measured and compensation adjusted frequently.

Other modifications will be apparent to those skilled in the art and, therefore, the invention is defined in the claims.